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AN EXPERIMENTAL STUDY ON THE BEHAVIOR OF RETROFITTED REINFORCED CONCRETE BEAMS IN FLEXURE

C Nagaraja
Reseach Scholar, Dept. of Civil Engineering,
Research Center, SIT, Tumakuru, India

Dr J K Dattatreya
Research Professor, Dept. of Civil Engineering, SIET, Tumakuru, India

Dr K P Shivananda
Professor, Dept. of Civil Engineering, SIET, Tumakuru, India

ABSTRACT

Concrete is the most widely used man made material with the characteristic that it has excellent resistance to water, the ease with which it can be casted and moulded to any desired shapes and sizes and the ready affordability of the materials with cheaper costs in the market. Moderate environmental conditions exist in considerable part of India, but highly industrialized zones, extreme hot and cold weather conditions and a large length of coastal line are present in which the concrete structures have to face severe aggressive environments. In these climatic zones, the concrete structures are deteriorated at an alarming rate. Fast track constructions, less regard to quality and poor workmanship have contributed to deterioration at a faster rate. In India, no reliable quantification of damage due to deteriorations has been made. A reliable study of the retrofitting of structures using various different materials newly introduced and available in the market has not been made so that their behavior under different loading conditions is not known. In this study, Experimental investigations have been carried out to the study the flexural behavior of retrofitted Reinforced concrete beams under two point loading conditions and compared with the flexural behavior of control beams.

Key words: Retrofitting, Flexure, Control Beam, FRP Wrapping, Cracks, Moment, Ductility.

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1. INTRODUCTION

India is the second largest producer of cement in the world next only China [1]. The construction of concrete structures is showing a severely raising trend with the booming cement production and the problem of early distress and deterioration of concrete structures has been reported in the recent years. In USA, it is estimated that the overall cost of repairing and replacing deteriorated concrete structures would be $200 billion [2]. Reliable estimates of deterioration of concrete are not available in India. However, it can be correlated to be about 35- 40% based on the data published by Cement Manufacturers' Association on end uses of cement used for repair and maintenance depending on market survey conducted in the late nineties [3]. This is considerably a very high figure indicating the alarming situation of distress, deterioration and durability. The repair is costly and even then the distressed structures need to be repaired. The following factors contribute to the need for repair and study:

- Fast track constructions due to immediate demand.
- Increase in stress levels due to adoption of reduced partial safety factors in the design.
- Changes in construction practices and growing public demand for improvement in infrastructure have led to construction of structures in severe and aggressive environments.
- Cements and cementitious materials which were used earlier are inadequate to meet the increasing demand in performance of present days.
- Several repair materials are available which are mostly proprietary products and hence very costly; but need to be characterized and there is a dearth of literature over post repair performance.
- The effectiveness of a repair is dependent on performance of repair material and also the characteristics of substrate material along with environmental conditions.

Even though the material characteristics of repair materials are helpful in the selection of appropriate repair material, they are insufficient to decide whether the chosen repair material enhances or restores the performance of the repaired component and durability of repair. Post repair data of repaired concrete structures is not much available even in countries like USA, Japan, UK,etc. In india, it is very much less and no authoritative and formalized codes of practice and accepted standards for performance criteria of various repair materials are present [4].

2. PRESENT WORK

The following methodology has been adopted for the present investigation carried out:

1. The experimental study involves the casting of three reinforced concrete beams. Among them, one beam was considered as control beam (CB) and another beam was considered as FRP wrapped Control beam (FRPCB) respectively. Remaining beam was pre cracked to the service load and then retrofitted using the material FRP. The loads carried, crack width, deflection, mode of failure etc, and were recorded for all the three beams. The performance and behavior of beam retrofitted with FRP and control beams were compared.
2. The materials used for the study are mentioned below:
   - Cement
   - Fine aggregate
   - Coarse aggregate
   - Water
   - Fiber reinforced polymer composites (FRP)

- Super plasticizer (Chemical admixture)
- Reinforcing steel

In this study, the Design mix of M30 concrete is used. For the preparation of design mix, ordinary Portland Cement of 53 Grade, M-sand, 20mm and downsize jelly is used. In the study, ordinary water supplied through taps has been used for the purpose. The superplasticizer as a chemical admixture sold under the commercial name Conplast SP430is used. Conplast SP430 is chloride free, superplasticizing admixture based on selected sulphonated naphthalene polymers. It is supplied as a brown solution which disperses in water instantly. HYSD bars of grade Fe-500 of 8 mm diameter were used for main reinforcement and as hanger bars and also for shear reinforcements. The present study of retrofitting of beams has been carried out using Carbon fiber reinforced polymer mat brought from BASF Construction Chemicals (India) Pvt. Ltd., Bengaluru.

Table 1 Properties of CFRP used for the present study

Technical data of Fiber	400 gsm
Modulus of elasticity	230kN/m^2
Tensile Strength	4900 N/m^2
Total weight of sheet	400 g/m^2
Density	1.8 g/cm^3
Thickness for static design	0.25 mm

Fiber reinforced polymer composites are a new class of composite material manufactured from fibers and resins. The composite consists of high strength fibers embedded in a matrix of polymer resin. The fibers typically used in FRP are glass, aramid and carbon. These fibers are all linearly elastic up to failure with no significant yielding compared to steel. The primary function of composite is to transfer the stress between the fibers to protect the surface of the fibers from mechanical abrasion and to provide a barrier against the environmental weathering.

Adhesives are used to attach the composites to other surfaces such as concretes. The most common adhesives are acrylics, urethanes and epoxies. Acrylics provide moderate temperature resistance with good strength and rapid curing whereas epoxies provide high bond strength with high temperature resistance. Several preparations have to be made before applying adhesives effectively. Careful surface preparation such as removing the cement paste, grinding the surface using a disc sander, removing the dust by air blower and careful curing are very critical to bond performance.

FRP sheets or plates can be bonded to reinforced concrete structural elements using various techniques such as external bonding, wrapping and near surface mounting. Retrofitting with externally bonded FRP sheets is the most widely used method for structural elements. FRP sheets/plates may be glued to the tension side of a structural member to provide flexural strength and glued to the sides of the web in beams to improve the shear strength. FRP sheets may be wrapped around the sides and bottom of beams and be wrapped around a column to provide confinement so that strength and ductility can be increased.

The main disadvantage of externally bonded FRP strengthening is the risk of fire, vandalism or accidental damages unless it is protected. A perceived disadvantage of using FRP is the relatively high cost of the materials. However, in comparison it may work out to be less costly with steel plate strengthening. The lack of accepted standards is a significant disadvantage.

3. EXPERIMENTAL STUDY AND OBSERVATIONS

In the experimental study, three reinforced concrete beams were casted. Among them, one beam was considered as control beam (CB) and another beam was retrofitted with FRP wrapping and considered as FRP wrapped Control beam (FRPCB). The remaining third beam was pre cracked to the service load and then retrofitted using the material i.e, FRP. The load carried, crack width, deflection, mode of failure etc, was recorded for all the three beams. The performance and behavior of beams retrofitted with FRP and control beams were compared.

3.1. Specimen details

The beam design has been carried out as per IS 456-2000 in limit state method.

Structural Design Details of RC Beams

Span - 1500 mm
Effective length - 1350 mm
Width - 100 mm
Overall depth - 150 mm
Effective Depth - 121mm
Number of main bars - 2 bars of 8 mm diameter
Area of tensile steel - 100.53mm^2
Hanger bars - 2 bars of 8 mm diameter
Shear reinforcement - 2 legged stirrups of 8 mm diameter at 100 mm c/c
Grade of concrete - M30
Grade of steel - Fe500
All the beams are designed as singly reinforced beams.

Table 2 Structural design details of RC Beams

Sl no.	Beam Specimen	Breadth B (mm)	Depth D (mm)	Shear reinforcement spacing in mm	A_{st} (mm^2)
1	CB	100	150	100	100.53
2	FRPCB	100	150	100	100.53
3	FRPRB	100	150	100	100.53

The abbreviations are as follows:

CB – Control Beam

FRPCB – FRP wrapped control beam

FRPRB – Beam pre cracked to the service load and then retrofitted using FRP material.

3.2. Methodology adopted for FRP material wrapping

The FRP sheets were wrapped to the tension zone of the beam on the underside as underlay using epoxy resin and the following procedure is adopted:

The surface of the beams was prepared by rubbing with sand papers and water washed. Then allowed to dry completely. Brushed again neatly for any dust to be removed before application of primer. The Primer is a 100% solid epoxy resin based primer for use on porous material substrate. Low viscosity enables effective penetration and sealing of porous substrate. The part A (Base) component is stirred first. The part B (Hardener) is added to part A and mixed well using slow speed stirrer for at least 3 minutes before use. The ratio followed was 100 (Base): 50 (Hardener) by weight. The epoxy primer was applied within 30 minutes and it was be allowed to dry for 6 hours. The MBrace primer was allowed to cure until tack free. The saturant is a 100% solid, blue pigmented, epoxy resin. The first coat of fully mixed saturant is applied to primed concrete surface using roller or brush.

The fabric of fiber sheet were carefully measured and cut in accordance with the specifications. Immediately after the application of epoxy saturant, the fiber sheet was adhered to the surface of the member by a uniform exertion of tensile force distributed across the entire width of fiber. All the air bubbles or air pockets were sqeezed out of the FRP sheet to give uniform and smooth final appearance by using rollers. Care was taken to ensure that no entrapped air be left in the FRP before the epoxy sets. Each individual layer was firmly bedded and adhered to the presiding layer or substrate.The fibers were coated with another layer of epoxy saturant for aesthetic blending, and protecting the layers from the environmental weathering.

The specimen with FRP composites was allowed to cure in atmosphere for about seven days to gain its strength after the final coat. The cured composite shall be having proper bond with the substrate and between the layers to ensure uniform thickness and impermeability.

3.3. Arrangement of test setup of beams in loading frame

The beams made ready for testing was properly arranged and positioned for loading in a loading frame system. The loading frame system consists of

- Loading frame
- Supports
- Loading jack
- Load transfer system

The beam was placed accurately on the roller support (simple support) as shown in the figure1. Care was exercised to keep it level for equal distribution of load on the beam. The two point loading with equal loads at equal distances from the centre of the beam was arranged.

Figure 1 Loading Frame and test set up

3.4. Testing procedure

Three dial gauges were used in the setup, i.e., one at the centre and the other two under the loading points at equal distances from the center. The initial readings of dial gauges were recorded in a tabular column before applying the load. The load was applied through a hydraulic jack in which the magnitude of load transferred could be read directly on the gauge provided.

The load was applied in regular equal increments i.e., 2 kN. At every increment of load, the dial gauge reading were recorded at the centre and under the two loadings. The observations were made for the appearance of cracks, the load at which the first crack appeared, the number of cracks, width of cracks and also the load at which the beam failed to take the further load, etc. and were recorded.

4. RETROFITTING OF DAMAGED REINFORCED CONCRETE BEAMS

To simulate damage of RC structures, one of the three RC beams was pre cracked and then retrofitted. Here, the loading was done and the beams were loaded until a crack width of 0.2 mm was reached. This load is taken as service load for the beams. Corresponding to this load, the appearance of crack was marked in the flexural zone. After cracking, the beam was unloaded and retrofitted using the FRP material.

The cracks appeared in the beam measured 5 to 7 cms from the soffit of the beam. The beam was retrofitted with FRP sheet. The cracks appeared and the retrofitting done there after with FRP.

Table 3 Test results of Control beam (CB)

Sl No.	Load (kN)	Mid span deflection (mm)	Moment (kN-m)	Crack width (mm)	Number of cracks
1	0	0	0	0	0
2	2	0.28	0.45	0	0
3	4	0.40	0.90	0	0
4	6	0.60	1.35	0.02	1
5	8	1.11	1.80	0.04	3
6	10	1.58	2.25	0.08	5
7	12	2.18	2.70	0.10	5
8	14	2.54	3.15	0.16	5
9	16	3.14	3.60	0.20	6
10	18	3.74	4.05	0.28	7
11	20	4.27	4.50	0.30	7
12	22	4.81	4.95	0.34	8
13	24	5.35	5.40	0.40	9
14	26	5.84	5.85	0.41	9
15	28	6.31	6.30	0.45	9
16	30	6.87	6.75	0. 54	9
17	32	7.49	7.20	0.58	11
18	34	10.42	7.65	0.80	11
19	36	15.54	8.10	2.00	12
20	38	20.18	8.55	2.50	12
21	34	22.12	7.65	3.00	13
22	32	23.08	7.20	3.05	15

Table 4 Test results of FRP wrapped Control beam (FRPCB)

Sl No.	Load (kN)	Mid span deflection (mm)	Moment (kN-m)	Crack width (mm)	Number of cracks
1	0	0	0	0	0
2	2	0.21	0.45	0	0
3	4	0.37	0.90	0	0
4	6	0.57	1.35	0	0
5	8	0.82	1.80	0	0
6	10	1.18	2.25	0	0
7	12	1.60	2.70	0.02	2
8	14	2.03	3.15	0.04	3
9	16	2.45	3.60	0.08	3
10	18	2.87	4.05	0.10	4
11	20	3.31	4.50	0.12	4
12	22	3.70	4.95	0.14	4
13	24	4.11	5.40	0.16	4
14	26	4.54	5.85	0.18	5
15	28	4.96	6.30	0.20	6
16	30	5.36	6.75	0.20	6
17	32	5.92	7.20	0.24	6
18	34	6.42	7.65	0.26	7
19	36	7.68	8.10	0..32	7
20	38	9.97	8.55	0.34	7
21	40	11.53	9.00	0.40	7
22	42	13.73	9.45	0.68	8
23	44	15.24	9.90	0.86	8
24	46	17.02	10.35	1.00	8
25	48	18.64	10.80	1.20	9
26	50	20.27	11.25	1.46	10
27	52	21.07	11.70	1.60	12
28	54	22.58	12.15	2.00	12
29	56	24.57	12.60	2.16	13
30	58	25.65	13.05	2.20	14
31	60	28.08	13.50	2.40	15
32	62	28.60	13.95	2.50	16
33	58	29.06	13.05	2.70	16
34	56	29.65	12.6	2.92	16

Table 5 Test results of FRP retrofitted beam (FRPRB) before retrofitting

Sl No.	Load (kN)	Mid span deflection (mm)	Moment (kN-m)	Crack width (mm)	Number of cracks
1	0	0	0	0	0
2	2	0.20	0.45	0	0
3	4	0.38	0.90	0	0
4	6	0.60	1.35	0.02	1
5	8	0.97	1.80	0.04	2
6	10	1.48	2.25	0.08	4
7	12	2.09	2.70	0.10	5
8	14	2.54	3.15	0.16	5
9	16	3.10	3.60	0.20	5

Table 6 Test results of FRP retrofitted beam (FRPRB) after retrofitting

Sl No.	Load (kN)	Mid span deflection (mm)	Moment (kN-m)	Crack width (mm)	Number of cracks
1	0	0	0	0	0
2	2	0.44	0.45	0	0
3	4	0.84	0.90	0	0
4	6	1.26	1.35	0	0
5	8	1.53	1.80	0	0
6	10	1.88	2.25	0.02	1
7	12	2.23	2.70	0.06	4
8	14	2.61	3.15	0.08	4
9	16	2.94	3.60	0.20	4
10	18	3.34	4.05	0.24	5
11	20	3.71	4.50	0.28	5
12	22	4.12	4.95	0.40	6
13	24	4.49	5.40	0.56	7
14	26	4.87	5.85	0.60	8
15	28	5.34	6.30	0.80	8
16	30	5.88	6.75	0.94	8
17	32	8.51	7.20	1.06	8
18	34	9.40	7.65	1.20	8
19	36	11.42	8.10	1.32	9
20	38	13.47	8.55	1.50	10
21	40	15.95	9.00	1.86	10
22	42	17.67	9.45	2.06	11
23	44	20.69	9.90	2.34	11
24	46	22.22	10.35	2.60	12
25	48	24.16	10.80	2.74	13
26	50	26.78	11.25	2.96	14
27	52	28.93	11.70	3.00	15
28	50	30.16	12.15	3.20	15
29	48	32.46	12.60	3.20	15
30	46	34.16	13.05	3.24	15

5. DISCUSSION OF RESULTS

The parameters discussed in the present study are as follows:

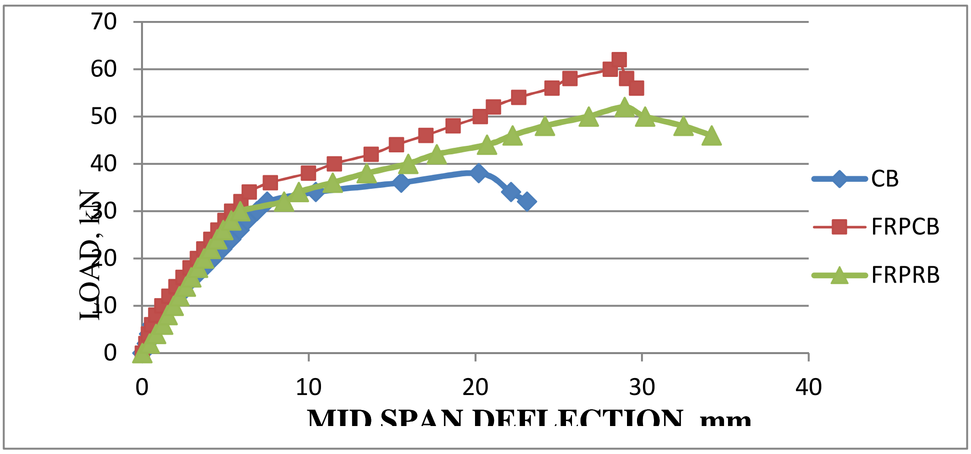
- Load deflection characteristics
- Cracking loads
- Service loads
- Ultimate loads
- Cracking characteristics
- Modes of failure

5.1. Experimental test results

A total number of three reinforced concrete beams were tested under two point incremental loading. The results for Control beam and FRP wrapped control beam were recorded. Incremental loading was applied on the beams and the load at which the first visible crack appeared was recorded as cracking load. The loading continued to be applied till the ultimate failure of beam resulted and recorded. The mid span deflections and the deflections under loads were recorded.

The retrofitted FRP beam (FRPRB) was pre cracked by loading up to the service load and then unloaded. After retrofitting, the beam was tested under two point loading. The cracking load, service load and ultimate load were recorded. The mid span deflections and the deflections under loads were recorded.

Load – Deflection characteristics



Graph 1 Load vs Deflection graph

Deflection is one of the limit states of serviceability basically dependent on parameters such as span, type and magnitude of loading, moment of inertia of cross section and the modulus of elasticity of the material i.e, concrete in the present case.

- From the graph, it can be seen that the beams exhibit a tri-linear behavior with distinct changes in slope at first crack and at yielding. After the yielding, the deflection continues with lesser resistance to loading.
- FRP wrapped beams have a behavior similar to control beam. They can sustain higher cracking load ranging from 10 to 12 kN and service load ranging from 16 to 28 kN.
- Compared to control beams, the beam wrapped with FRP sheet exhibited higher stiffness. This increase in stiffness is attributed to slightly increased moment of inertia and the initiation and widening of cracks being controlled in the tension zone due to adherence of FRP integral with concrete. The deflection of FRP control beams (FRPCB) beams at failure (28.6 mm) is higher than that of control beam (CB) deflections (20.18 mm). The control beam (CB) showed a deflection of 3.14 mm at service load (16kN) while the FRP beam showed a deflection of 2.45 mm at 16 kN.
- The FRP bonded beams have exhibited a integral action with concrete and FRP indicating perfect composite behavior without any debonding upto failure.
- Due to better stitching achieved, the crack formation is delayed in FRP retrofitted beam. The FRP retrofitted beam also showed higher ultimate load due to high tensile strength of FRP and hence higher moment carrying capacity compared to control beam.

5.2. Load carried by the beams at various stages

Table 7 Load carried at various stages by beams

Sl No.	Specimen ID	First crack load P_{cr} (kN)	Service load P_{Sl} (kN)	Ultimate load P_{ul} (kN)
1	CB	6	16	38
2	FRPCB	12	28	62
3	FRPRB	10	16	52

The retrofitted beam after craking, the FRPRB has shown the ultimate load carrying capacity increased by almost 37% more than the control beam load carrying capacity. By mere retrofitting with FRP to a control beam, the beam load carrying capacity is observed to be increased by 63% more than the control beam which shows that the FRP can be used as one of the best retrofitting materials for retrofitting the structures.

5.3. Cracking moment

The moment at which the uncracked beam reaches its limit upto cracking is termed as cracking moment. During the test, the loads on the beam specimens at which the first cracking appeared were recorded and the cracks were visibly observed with a hand held microscope. From these values, the cracking moments were determined. The cracking moment for the various beam specimens are mentioned as follows in table 8:

Table 8 Cracking moments in the beam specimens

Sl No.	Specimen ID	Cracking Moment, M_{cr} (kN-m)
1	CB	1.35
2	FRPCB	2.70
3	FRPRB	2.25

The cracking moment of FRPCB is the hghest and that of FRPRB specimens are higher due to higher moment of inertia compared to control beam and the resistance to crack formation.

Deflections at various load stages:

Table 9 Deflections in the beam specimen at various loads

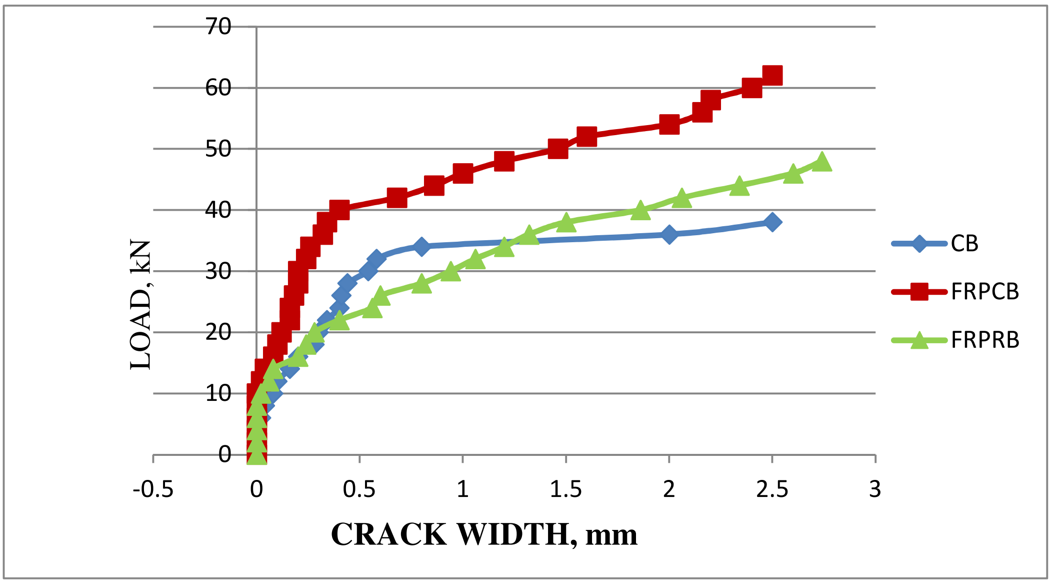
Sl No.	Specimen ID	Deflection at crack load (mm)	Deflection at Service load (mm)	Deflection at ultimate load (mm)
1	CB	0.60	3.14	20.18
2	FRPCB	1.60	4.96	28.60
3	FRPRB	1.88	2.94	28.93

- Deflections at crack load and service load is higher for FRP beams due to better integral stitching achieved by the externally bonded reinforcements in the form of repair materials.
- Deflection at ultimate load is higher for FRP as the ultimate strain capacity of FRP is 0.02 and the internal steel reinforcement fractured well before the value is reached. Therefore the failure strain in internal steel governs the ultimate deflection.

5.4. Crack Width

Using a hand microscope, the crack width for different load increments were measured and the readings were tabulated. A graph of load vs crack width is plotted as shown below:

- After the appearance of the first crack, the crack width continue to increase with increase in load linearly in all the beam specimens
- A remarkable increase in crack width is seen after the service load upto ultimate load.
- The number of cracks in FRP bonded beams was found to be less compared to control beam specimen.
- In the FRPRB specimen, cracks appeared from the previous cracks in the beam which were pre cracked to service load before retrofitting.



Graph 2 Load vs Crack width

5.5. Failure mode and Crack pattern

Cracking is a most common phenomenon in reinforced concrete when the tensile stress in concrete exceeds its limiting value and inability of the concrete to take up tension. The cracks form when the tensile strain reaches the limit of the order of 0.0002 to 0.0005.

After the first visible crack, the number of cracks in the flexural tension zone increases with every increment in load. The number of flexural cracks stabilized beyond the yield load and the cracks at the mid span opened widely with the yielding of steel thereafter. There is a significant deflection observed at ultimate load in all the beams.

Yielding of the tensile steel followed by the crushing of concrete in the compression zone caused the failure in the beams. In general, the failure modes of all beams and the crack pattern at various stages were observed to be similar.

The propagation of cracks and failure mode of beams could be characterized into three stages:

- The cracks initiated and showed upward mobility.
- The cracks already appeared widened and also propagated upwards along with the appearance a few more cracks in the flexure zone.
- The increase in the crack width is observed without the formation of new cracks in the final stages up to failure.

The failure was significantly characterized with wide cracks and large deflections.

6. CONCLUSIONS

The following conclusions are drawn based on the observations of the above mentioned results obtained:

- FRPCB beam specimen showed the highest cracking load among all the beams, i.e about 20% more than FRPRB 100% more than CB specimen. Even a cracked beam can be strengthened beyond its original flexural capacity (from 6kN of CB to 10kN of FRPRB) by 67%. Maintaining the stitching and bonding of FRP sheets efficiently.
- The number of cracks that appeared in CB specimen at ultimate load value was 12. At the same load level for FRPCB beam, the number of cracks was 10. But with loading continued up to 62 kN, the number of cracks were only 16. Hence for strengthening of any structure from its original flexural capacity to be increased substantially, FRP wrapping can be recommended. Even the retrofitted FRPRB specimen showed a ultimate load value of 52 kN with a number of 15 cracks The flexural strength and the resistance to cracking have been enhanced substantially by FRP wrapping. Hence in situations where flexural capability and ductility of a reinforced concrete member needs to be increased, FRP wrapping can be suitably recommended.
- The minimum deflection at cracking load among the beams was recorded for CB specimen. The minimum deflection at service load among the beams was recorded for FRPRB (2.94 mm) specimen. This establishes that the FRP wrapped beams showed better stiffness at earlier stages in comparison. It can be stated FRP wrapping provides more stiffness at earlier stages and better ductility at later stages of loading above service load.
- The tensile strength of FRP fibers efficiently participated in taking the load even after concrete and steel yielded and FRP fibers imparted the necessary ductility required in demanding situations. The FRPRB allowed crack width up to 3mm at its ultimate load of 52 kN and up to which continued to bear the load without failure.

From the experimental study conducted, it can be concluded that for retrofitting of RC structures where the increase in flexural capacity, stiffness, decrease in crack width and better ductility is required, the FRP wrapping can be recommended.

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